The Impact of Incapacitation of Multiple Critical Sensor Nodes on Wireless Sensor Network Lifetime

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***Abstract*—Wireless Sensor Networks (WSNs) are envisioned to be utilized in many application areas such as critical infrastructure monitoring, therefore, WSN nodes are potential targets for adversaries. Network lifetime is one of the most important performance indicators in WSNs. Possibility of reducing the network lifetime significantly by eliminating a certain subset of nodes through various attacks will create the opportunity for the adversaries to hamper the performance of WSNs with a low risk of detection. However, the extent of reduction in network lifetime due to elimination of a group of critical sensor nodes has never been investigated in the literature. Therefore, in this study, we created two novel algorithms based on a Linear Programming (LP) framework to model and analyze the impact of critical node elimination attacks on WSNs and explored the parameter space through numerical evaluations of the algorithms. Our results show that critical node elimination attacks can significantly shorten the network lifetime.**

***Index Terms*—wireless sensor networks, linear programming, network lifetime, sensor node incapacitation, DoS, physical attack**

I. Introduction

The concept of a sensing system created by multiple low-cost and tiny devices for information extraction over a predetermined deployment area is, generally, known as Wireless Sensor Networks (WSNs) [1]. Some of the application areas for WSNs are remote monitoring, military applications, automation systems, smart grid, underwater surveillance, and agriculture (among many others) [2], [3]. Providing useful service for extended durations is, inarguably, an essential feature of WSNs, hence, network lifetime is, arguably, the most important Quality-of-Service (QoS) metric for them [4].

Like most networked communication systems, WSNs are to be protected against potential security threats. Several characteristics of WSNs like resource constraints, ad hoc mode of operation, and lack of physical protection (due to harsh operation conditions) make them especially vulnerable against different types of attacks from physical layer to application layer [5]. Since prolonging the network lifetime is the most important objective in WSN design, security threats with the purpose of reducing the energy efficiency of the system constitute an important class of security attacks against such networks. Denial of Sleep attacks, which is a special type of Denial-of-Service (DoS) attacks, are directed against WSNs to deny the sensors the possibility of entering into the sleep mode so that the network breaks down prematurely [6], [7].

To achieve the longest possible lifetime for WSNs, nodes should cooperate in relaying the data acquired from the environment. It is possible to design a novel attack type to reduce the lifetime of the network by incapacitating a specific group of sensor nodes that are critical in achieving optimal energy balancing (*i.e.*, lifetime reduction by incapacitating critical nodes). Such an attack has the potential to reduce network lifetime disproportionately with the number of sensor nodes eliminated [8]. Elimination of nodes can be achieved through physical destruction of a limited number of critical sensor nodes or remote node capture attacks by adversaries. Furthermore, it is also possible that critical sensor nodes can be incapacitated due to natural risks such as landslides. Note that the definition of critical nodes in our study is different from the general use in WSN literature where elimination of critical nodes results in network disconnection [9] whereas in our case, we assume that the network is strongly connected, therefore, incapacitation of a few nodes do not result in network partitioning.

The original contributions of this study are enumerated as follows:

1) We identified an important research topic left uninvestigated in the literature which is the investigation of the change in network lifetime due to the elimination of a group of critical sensor nodes.
2) To analyze this problem under optimal operating conditions we constructed a novel Linear Programming (LP) framework and designed two algorithms based on the LP model. The exact algorithm has a prohibitively high computational complexity whereas the approximate algorithm has polynomial time complexity.
3) We explored the parameter space through the extensive numerical analysis of our algorithms and characterized the extent of lifetime decrease/increase due to the critical node elimination. Furthermore, we showed that the approximate algorithm and the exact algorithm give close results.

II. Model

In our network model, there exists a single base station at the center of the disc shaped network deployment area and multiple sensor nodes (*i.e.*, N_S sensor nodes), which are randomly distributed. Each sensor node-i generates s_i amount

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of data (256 bits) periodically (60 s) and all generated data terminate at the base station. All sensor nodes can act as relays for forwarding data towards the base station. The network topology is represented by a directed graph, $G = (V, A)$ where V is the set of all sensor nodes and the base station is defined as node-1. We also define a set W which includes all nodes except node-1 ($W = V \setminus \{1\}$). $A = \{(i, j) : i \in W, j \in V - i\}$ is the set of links. Note that by definition no node sends data to itself. The objective function is the maximization of t (the minimum lifetime of all sensor nodes). We adopt the network lifetime definition given in [4], which is the time when the first sensor node exhausts all of its battery power. Since the objective is the maximization of the lifetime which is common for all nodes, all sensor nodes cooperate to extend the lifetime as much as possible through network wide energy balancing, hence, all nodes deplete their batteries at the end of the network lifetime. The amount of data flowing from node-i to node-j is represented by variable f_{ij}. The LP model is presented in Figure 1.

Maximize t
Subject to:

$$f_{ij} \geq 0 \;\forall (i, j) \in A \tag{1}$$

$$\sum_{j \in V} f_{ij} - \sum_{j \in W} f_{ji} = \begin{cases} s_i t & \forall i \in W \\ -\sum_{j \in W} s_j t & i = 1 \end{cases} \tag{2}$$

$$\sum_{j \in V} E^{opt}_{tx,ij} f_{ij} + E_{rx} \sum_{j \in W} f_{ji} \leq e_i \;\forall i \in W \tag{3}$$

$$e_i = E_{init} \;\forall i \in W \tag{4}$$

Fig. 1: The LP model for lifetime maximization.

Eq. 1 states that all flows are non-negative. Eq. 2 is the flow balancing constraint which states that for all nodes except the base station, the difference between the amount of data flowing out of node-i and the amount of data flowing into node-i is equal to the amount of total data generated by node-i. Furthermore, all generated data by the sensor nodes terminate at the base station (*i.e.*, node-1). Eq. 3 presents the energy dissipation constraint for sensor nodes. The amount of energy dissipated on transmission and reception is limited by the initial energy of sensor nodes (e_i). Furthermore, each sensor node is assigned with equal initial energy at the beginning of the network operation (*i.e.*, E_{init} = 3 J) as stated in Eq. 4. The optimal amount of energy to transmit one bit of data over a distance (d_{ij}, the distance between node-i and node-j) is represented by $E^{opt}_{tx,ij}$ and the energy to receive one bit of data is represented by E_{rx}. Experimentally determined energy dissipation and transmission ranges for Mica2 mote platform are presented in Table I [10] where energy consumption for transmission power level-l is denoted as $E_{tx}(l)$ and the maximum transmission range at this level is indicated as $R_{max}(l)$. Note that, transmission power takes a value from a finite set denoted as S_L (*i.e.*, there are just 26 power levels to choose from). While the energy required for transmitting one bit depends on the distance between source and destination, the energy required for receiving does not and it has a constant value (E_{rx} = 0.922 J/bit). If d_{ij} is greater than maximum transmission range, $R_{max}(26)$ = 82.92 m, no data can be sent from node-i to node-j. Each sensor node chooses its optimal transmission energy for each outgoing link as presented in Eq. 5.

TABLE I: Transmission energy consumption ($E_{tx}(l)$ – nJ/bit) and transmission range ($R_{max}(l)$ – m) at each power level-l for the Mica2 mote as a function of power level [10].

l	$E_{tx}(l)$	$R_{max}(l)$	l	$E_{tx}(l)$	$R_{max}(l)$
1 (l_{min})	671.88	19.3	14	843.75	41.19
2	687.50	20.46	15	867.19	43.67
3	703.13	21.69	16	1078.13	46.29
4	705.73	22.69	17	1132.81	49.07
5	710.94	24.38	18	1135.42	52.01
6	723.96	25.84	19	1179.69	55.13
7	726.56	27.39	20	1234.38	58.44
8	742.19	29.03	21	1312.50	61.95
9	757.81	30.78	22	1343.75	65.67
10	773.44	32.62	23	1445.31	69.61
11	789.06	34.58	24	1500.01	73.79
12	812.50	36.66	25	1664.06	78.22
13	828.13	38.86	26 (l_{max})	1984.38	82.92

$$E^{opt}_{tx,ij} = \left\{ \begin{array}{c} E_{tx}(1) \; if \; d_{ij} \leq R_{max}(1) \\ E_{tx}(l) \; if \; R_{max}(l-1) < d_{ij} \leq R_{max}(l) \\ \infty \; if \; d_{ij} > R_{max}(26) \end{array} \right\} \tag{5}$$

We employ the LP model for network lifetime maximization as a building block in the construction of our algorithms for determining the most critical nodes in the network. Exclusion of these nodes from the network topology will reduce the network lifetime the most. Note that we assume the network is strongly connected and elimination of nodes (up to a certain limit) will not result in network partitioning. If we want to determine a single critical node which reduces the network lifetime the most, we can run the LP model for the given topology with $(N_S - 1)$ sensor nodes for N_S times (*i.e.*, one node at a time is removed from the topology and the lifetime is computed). Thus, the most critical node will be the node that gives the lowest lifetime when removed. Furthermore, removal of certain nodes will not reduce the network lifetime at all. To the contrary, removal of certain nodes will result in a net increase in network lifetime. Although, determining the single most critical node can be done in N_S runs of the LP model, determining a group of critical sensors nodes that reduce the lifetime most is not straightforward. We can use a sequential algorithm (Algorithm 1) to determine N_C critical nodes which determines the most critical node in N_S runs then proceeds with remaining nodes to determine the second most critical node in another $N_S - 1$ runs until N_C most critical nodes are determined in N_C steps in a total of $N_C N_S - \frac{N_C(NC-1)}{2}$ runs of the LP model. Alternatively we can determine the most critical N_C nodes by considering their combined impact on network lifetime (Algorithm 2). To do so all combinations of N_C nodes among the total N_S nodes should be removed from the network and the lifetime values in the absence of all groups should be computed which necessitates a total of $\binom{N_S}{N_C} = \frac{N_S!}{N_C!(N_S - N_C)!}$ runs of the LP model.

Algorithm 1 takes as input a network topology as a graph of nodes and edges ($G = (V, A)$), the number of critical nodes

Algorithm 1: Sequential Critical Node Selection

Input : G=(V, A): a network topology graph
N_C: the number of critical nodes
mod: $'min'$ or $'max'$ for minimizing or maximizing the network lifetime with the removal of critical nodes
Output: C={(v_j, lt_j): ordered set of critical nodes v_j, $v_j \in V$, $1 \leq j \leq n$, and the network lifetime lt_j when v_1 to v_j removed from G }

1 **for** k=*1 to* N_C **do**
2   **if** mod=$'max'$ **then**
3     $C_k.lifeTime = 0$
4   **else**
5     $C_k.lifeTime = \infty$
6   **end**
7   **foreach** $v_i \in V$ *for* $1 \leq i \leq |V|$ **do**
8     $lt_i \leftarrow lifeTime(G \backslash v_i)$
9   **if** *(mod='max' and* $lt_i > C_k.lifeTime$*) or (mod='min' and* $lt_i < C_k.lifeTime$*)* **then**
10       $C_k.criticalNode = v_i$
11       $C_k.lifeTime = lt_i$
12   **end**
13   **end**
14   ▷ remove the critical node from G, removal of which gives maximizes/minimizes lifetime
15   $G \leftarrow G \backslash C_k.criticalNode$
16 **end**
17 **return** C

Algorithm 2: Bulk Critical Node Selection

Input : G=(V, A): a network topology graph
N_C: the number of critical nodes
mod: $'min'$ or $'max'$ for minimizing or maximizing the network lifetime with the removal of critical nodes
Output: C={(v_j): $v_j \in V$, $1 \leq j \leq n$ }: set of critical nodes
lt: min. or max. lifetime of G after removal of critical nodes C

1 $C \leftarrow \phi$
2 **while** $tempC$=$chooseNextNNodes(G, N_C)$ **do**
3   **if** mod=max **then**
4     $lt = 0$
5   **else**
6     $lt = \infty$
7   **end**
8   $tempLT \leftarrow lifeTime(G \backslash tempC)$
9   **if** *(mod=max and tempLT > lt) or (mod=min and tempLT < lt)* **then**
10     $C \leftarrow tempC$
11     $lt \leftarrow tempLT$
12   **end**
13 **end**
14 **return** C, lt

to be found (N_C), and the mode of execution (mod) that determines whether a lifetime minimization or maximization objective is sought. In return Algorithm 1 finds an ordered set of N_C critical nodes (C) and the network lifetimes when each critical node is removed from G in the given order in C. If the $mode$ is 'max' then the network lifetime found is maximum or minimum in the case the $mode$ is 'min'. The algorithm iterates N_C times (line 1) and in each iteration finds one critical node (line 10-11) that minimizes or maximizes the network lifetime (line 8-9) when it is removed from the network (line 8) by iterating over all nodes (line 7). Algorithm 2 finds N_C critical nodes at once. In this case N_C critical nodes are removed from the network altogether (line 8) which minimizes/maximizes the network lifetime.

III. Analysis

In this section, we explore the impact of elimination of the most critical sensor nodes on WSN lifetime through numerical evaluations of the Algorithm 1 and Algorithm 2 which utilize the LP model for lifetime maximization. We use General Algebraic Modeling System (GAMS) with XPRESS solver for the numerical analysis of the LP problems.

In Table II, we present network lifetime change as a function of network radius (R_{net}) for Algorithm 1 ($N_S = 50$). Negative values indicate decrease in network lifetime when compared to the original network topology (before elimination of any sensor nodes) and positive values indicate increase in network lifetime. Average lifetime decrease/increase by the removal of a single node is denoted as AMD-1/AMI-1 whereas average lifetime decrease/increase due the removal of two nodes are denoted as AMD-2/AMI-2 and so on. Furthermore, the maximum lifetime decrease/increase due to sensor node removals (*i.e.*, the largest value encountered in all runs) are denoted as MD-N_C/MI-N_C.

We present the averages of 100 runs for statistical significance. More precisely stated, we generate a random topology and use this topology for the analysis of MD-1, MD-2, MD-3, MD-4, and MD-5. Likewise, analyses of MI-N_C are done on the same topology. This process is repeated for 100 random topologies. Therefore, for a given random topology, lifetime decrease/increase with a higher N_C is at least as high as the lifetime decrease/increase with a lower N_C. Consequently, by the design of the experiment, AMD-($k+1$)/AMI-($k+1$) is higher than or equal to AMD-(k)/AMI-(k).

The impact of elimination of critical nodes is more severe in sparser networks (*e.g.*, AMD-2 values are 6.88%, 24.57%, and 35.14% for networks with radii 100 m, 150 m, and 200 m, respectively). The average decrease in network lifetime can be as high as 20.17% (AMD-1) and 63.98% (AMD-5) when $R_{net} = 200$ m. As expected, as the number of critical nodes increase the impact on the lifetime also increases. For example, average lifetime decreases with 175 m radius are 17.95%, 43.45%, and 58.52% for $N_C = 1$, 3, and 5, respectively. The maximum decrease for a given parameter set is much higher than the average decrease value throughout the parameter space. For example, the maximum reduction in network lifetime with $R_{net} = 200$ m and $N_C = 2$

TABLE II: Change in network lifetime (%) wrt. the original network (*i.e.*, the network before the removal of any sensor nodes) for Algorithm 1. Results are presented in $\mu \pm \sigma$ format where μ is the ensemble average and σ is the 95% confidence interval.

R_{net} (m)	**AMD-1**	**AMD-2**	**AMD-3**	**AMD-4**	**AMD-5**	**MD-1**	**MD-2**	**MD-3**	**MD-4**	**MD-5**
100	-3.40±0.21	-6.88±0.41	-10.52±0.66	-14.23±0.94	-18.21±1.32	-8.44	-17.43	-26.71	-36.55	-46.66
125	-6.78±0.67	-13.53±1.21	-20.34±1.90	-26.74±2.27	-33.15±2.69	-30.13	-40.62	-55.28	-71.45	-84.70
150	-11.99±1.36	-24.57±2.47	-35.78±3.22	-44.79±3.27	-53.19±3.37	-48.15	-56.26	-68.22	-78.39	-85.20
175	-17.95±2.44	-32.35±3.35	-43.45±3.99	-51.70±4.22	-58.52±4.45	-59.16	-68.53	-77.06	-80.69	-86.32
200	-20.17±3.41	-35.14±5.11	-48.57±5.80	-56.89±6.27	-63.98±6.54	-65.19	-72.82	-79.91	-83.19	-86.35
R_{net} (m)	**AMI-1**	**AMI-2**	**AMI-3**	**AMI-4**	**AMI-5**	**MI-1**	**MI-2**	**MI-3**	**MI-4**	**MI-5**
100	3.40±0.18	6.75±0.28	10.19±0.40	13.69±0.52	17.26±0.61	6.71	12.27	18.29	24.80	31.20
125	3.10±0.20	6.25±0.37	9.51±0.56	12.90±0.75	16.43±0.94	7.08	13.18	17.81	25.03	32.06
150	3.08±0.24	6.15±0.43	9.34±0.63	12.61±0.83	15.98±1.02	8.46	14.47	18.71	25.33	32.88
175	3.67±0.69	6.69±1.62	11.92±2.63	16.03±3.59	17.60±3.95	18.79	23.65	27.46	34.97	41.25
200	3.99±0.60	7.06±1.24	12.15±1.83	17.10±2.29	18.09±2.80	27.94	37.91	43.47	57.26	61.09

(*i.e.*, MD-2) is 72.82% whereas the average decrease for the same network is 35.14%. The maximum reduction in network lifetime increases as N_C increases up to 86.35%.

It is possible that we can remove some of the nodes so that network lifetime increases. The reason for such behavior is that certain relay nodes dissipate unproportionately high energy to relay some nodes' data and when these nodes are eliminated the burden of relaying on some relay nodes are lightened. Average increase in network lifetime can be as low as 3.08% (AMI-1 with $R_{net} = 150$ m) and can be as high as 18.09% (AMI-5 with $R_{net} = 200$ m). On the other hand, the maximum increment in the lifetime is not high as the maximum decrement in the lifetime (*i.e.*, maximum increase in lifetime is 61.09% for MI-5 and $R_{net} = 200$ m).

We obtain results by using Algorithm 2 for $N_C = 1$ and 2 with the same network radii and N_S values. We cannot obtain results by using Algorithm 2 for $N_C > 2$ due to the prohibitively high computational complexity. For example, when $N_C = 2$ and $R_{net} = 200$ m computation time for Algorithm 1 is less than 40 s whereas the computation time for Algorithm 2 is more than 1200 s. Due to the lack of space we do not present the results for Algorithm 2. Nevertheless, for all of the numerical evaluations, we found that both algorithms give close results (*e.g.*, average lifetime decreases obtained with Algorithm 1 and Algorithm 2 are 6.8812% and 6.8817% for AMD-2 with $R_{net} = 100$ m). Hence, utilization of the sequential search algorithm is preferable over the bulk search algorithm because computational complexity of the bulk search is much higher than the sequential search.

We investigate the features of critical nodes (*e.g.*, proximity to the base station, number of neighbors, number of active links, amount of relayed data, and energy dissipated on relaying) which can be used to identify them. We found that the probability of a node closer to the base station to be a critical node is higher than a farther away node, however, such a measure is not decisive (*i.e.*, although nodes closer to the network periphery have a lower probability of being a critical node, this probability is still well above zero). Likewise, all the aforementioned features fail to identify critical nodes without a non-negligible level of ambiguity.

IV. Conclusion

Wireless Sensor Networks (WSNs) are prone to sensor node failures due to many reasons such as security threats, natural hazards, hardware/software errors. Incapacitation of a group of sensor nodes can reduce the network lifetime significantly even if such networks are operated by using ideal routing schemes to maximize the network lifetime. Determination of the extent of network lifetime change (decrease/increase) is therefore an important research question that has not been investigated in the literature to the best of our knowledge. In this study, we constructed two algorithms (sequential search and bulk search algorithms) to investigate the impact of elimination of critical nodes on WSN lifetime. Both algorithms are based on a novel LP model. Our results reveal that the average network lifetime decrease due the elimination of critical nodes can be as high as 64.0% with a group of five critical nodes. Furthermore, maximum lifetime reduction is upper bounded by 86.4% ($N_C = 5$).

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